

Invited talk at the TJNAF Users Workshop  
 Newport News, June 15-18, 1998  
 ADP-98-36/T309

## Recent results from QMC relevant to TJNAF

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We review recent calculations using the quark meson coupling model which should be of particular interest at Jefferson Lab. In particular, we discuss the change in the proton electric and magnetic form factors when it is bound in a specific shell model orbit. Modern quasi-elastic electron scattering experiments should be able to detect effects of the size predicted. We also examine the mean field potential felt by an  $\omega$  in a finite nucleus, concluding that the  $\omega$  should be bound by between 50 and 100 MeV.

### I. INTRODUCTION

Whether or not quark degrees of freedom play a significant role in nuclear theory is one of the most fundamental questions in strong interaction physics. Tremendous efforts have been devoted to the study of medium modifications of hadron properties [1]. The idea that nucleons might undergo considerable change of their internal structure in a baryon-rich environment is supported by our understanding of asymptotic freedom in QCD. In particular, at sufficiently high density one expects a transition to a new phase of matter where quarks and gluons are deconfined and it seems unlikely that there would be no indication of this below the critical density. There has also been quite a bit of encouragement from experiment, including the discovery of the variation of nucleon structure functions in lepton deep-inelastic scattering off nuclei (the nuclear EMC effect) [2], the quenching of the axial vector coupling constant,  $g_A$ , in nuclear  $\beta$ -decay [3], and the missing strength of the response functions in nuclear quasielastic electron scattering [4].

There have been several effective Lagrangian approaches in the literature dealing with modifications of the nucleon size and electromagnetic properties in medium [5,6]. All of these investigations have found that nucleon electromagnetic form factors are suppressed and the rms radii of the proton somewhat

increased in bulk nuclear matter. In Ref. [6], we examined medium modifications of nucleon electromagnetic properties in nuclear matter, using the quark-meson coupling model (QMC) [7,8]. The self-consistent change in the internal structure of a bound nucleon was found to be consistent with the constraints from  $y$ -scaling data [9] and the Coulomb sum rule [10]. Here we present a preliminary report on our investigations of the electromagnetic form factors for a nucleon bound in specific, shell model orbitals of realistic, finite nuclei. This is of direct relevance to quasielastic scattering measurements underway at TJNAF [11].

One of the most obvious changes in a particle's in-medium properties is its effective mass and the medium modification of the light vector ( $\rho$ ,  $\omega$  and  $\phi$ ) meson masses has been investigated extensively by many authors [12]–[17]. It has been suggested that dilepton production in the nuclear medium formed in relativistic heavy ion collisions, can provide a unique tool to measure such modifications as meson mass shifts. For example, the experimental data obtained at the CERN/SPS by the CERES [18] and HELIOS [19] collaborations has been interpreted as evidence for a downward shift of the  $\rho$  meson mass in dense nuclear matter [20]. To draw a more definite conclusion, measurements of the dilepton spectrum from vector mesons produced in nuclei are planned at TJNAF [21] and GSI [22].

Recently, a new method to study meson mass shifts in nuclei was proposed by Hayano *et al.* [23]. Their suggestion is to use the ( $d$ ,  $^3He$ ) reaction to produce  $\eta$  and  $\omega$  mesons with nearly zero recoil momentum. If the meson feels a large enough, attractive (Lorentz scalar) force inside a nucleus it will form a meson-nucleus bound state – of course, there is a cancellation of the mean field vector potential for a quark-anti-quark pair. Hayano *et al.* [24] estimated the binding energies for various  $\eta$ -mesic nuclei. They also calculated some quantities for the  $\omega$  meson case. Their  $\eta$ -nucleus optical potential was calculated to first-order in density, using the  $\eta$ -nucleon scattering length as input. We recently investigated this problem [25], using QMC to study whether it is possible to form  $\eta$ - and/or  $\omega$ -nucleus bound states in  $^{16}O$ ,  $^{40}Ca$ ,  $^{90}Zr$  and  $^{208}Pb$ , as well as  $^6He$ ,  $^{11}B$  and  $^{26}Mg$ . The latter three nuclei correspond to the proposed experiment at GSI – i.e., the reactions,  $^7Li(d, ^3He)_{\eta/\omega}^6He$ ,  $^{12}C(d, ^3He)_{\eta/\omega}^{11}B$  and  $^{27}Al(d, ^3He)_{\eta/\omega}^{26}Mg$ . Here we shall briefly report our results for the  $\omega$  case, which is again of direct interest at Jefferson Lab.

## II. THE QUARK MESON COUPLING MODEL

The details of the derivation of the Quark Meson Coupling model (QMC) for finite nuclei may be found in Ref. [8]. Here we briefly summarize the

essential points. At least as far as the single particle energies are concerned, the QMC model for spherical finite nuclei, in mean-field approximation, can be summarized in an effective Lagrangian density [8]

$$\begin{aligned} \mathcal{L}_{QMC} = & \bar{\psi}(\vec{r})[i\gamma \cdot \partial - m_N + g_\sigma(\sigma(\vec{r}))\sigma(\vec{r}) - g_\omega\omega(\vec{r})\gamma_0 \\ & - g_\rho \frac{\tau_3^N}{2}b(\vec{r})\gamma_0 - \frac{e}{2}(1 + \tau_3^N)A(\vec{r})\gamma_0]\psi(\vec{r}) \\ & - \frac{1}{2}[(\nabla\sigma(\vec{r}))^2 + m_\sigma^2\sigma(\vec{r})^2] + \frac{1}{2}[(\nabla\omega(\vec{r}))^2 + m_\omega^2\omega(\vec{r})^2] \\ & + \frac{1}{2}[(\nabla b(\vec{r}))^2 + m_\rho^2b(\vec{r})^2] + \frac{1}{2}(\nabla A(\vec{r}))^2, \end{aligned} \quad (1)$$

where  $\psi(\vec{r})$ ,  $\sigma(\vec{r})$ ,  $\omega(\vec{r})$ ,  $b(\vec{r})$ , and  $A(\vec{r})$  are the nucleon,  $\sigma$ ,  $\omega$ ,  $\rho$ , and Coulomb fields, respectively. Note that only the time components of the  $\omega$  and neutral  $\rho$  fields are kept in the mean field approximation. These five fields now depend on position  $\vec{r}$ , relative to the center of the nucleus. The spatial distributions are determined by solving the equations of motion self-consistently.

At the level of the effective Lagrangian density, the key difference between QMC and QHD [26] lies only in the  $\sigma NN$  coupling constant, which depends on the scalar field strength in QMC while it remains constant in QHD. The coupling constants  $g_\sigma(0)$ ,  $g_\omega$  and  $g_\rho$  are fixed to reproduce the saturation properties and the bulk symmetry energy of nuclear matter. The only free parameter,  $m_\sigma$ , which controls the range of the attractive interaction, and therefore affects the nuclear surface slope and its thickness, is fixed by fitting the experimental charge rms radius of  $^{40}Ca$ , while keeping the ratio  $g_\sigma/m_\sigma$  intact, as constrained by the nuclear matter properties. We note that one of the major successes of the model in nuclear matter is that it always produces a value for the nuclear incompressibility that is in reasonable agreement with experiment.

### III. FORM FACTOR MODIFICATIONS IN MEDIUM

Of course, the main difference between QMC and conventional treatments of nuclear structure is that in QMC the internal structure of the “nucleon” self-consistently adjusts to the local medium in which it sits. The quark wave function, as well as the nucleon wave function (both are Dirac spinors), are determined once a solution to equations of motion are found. The electromagnetic form factors for a proton bound in a specific orbit  $\alpha$ , in local density approximation, are simply given by

$$G_{E,M}^\alpha(Q^2) = \int G_{E,M}(Q^2, \rho_B(\vec{r}))\rho_{p\alpha}(\vec{r}) d\vec{r}, \quad (2)$$

where  $G_{E,M}(Q^2, \rho_B(\vec{r}))$  is the density-dependent form factor of a “proton” immersed in nuclear matter with a local baryon density,  $\rho_B(\vec{r})$ . Using the calculated nucleon shell model wave functions, the local baryon density and the local proton density in the specified orbit  $\alpha$ , are easily evaluated.

The notable medium modifications of the quark wavefunction inside the bound “nucleon” in QMC include a reduction of its frequency and an enhancement of the lower component of the Dirac spinor. As in earlier work, the corrections arising from recoil and center of mass motion for the bag are made using the Peierls-Thouless projection method, combined with Lorentz contraction of the internal quark wave function, and the perturbative pion cloud is added afterwards [27]. Additional off-shell form factors and possible meson exchange currents have been omitted in the present, exploratory investigation. The resulting nucleon electromagnetic form factors agree with experiments quite well in free space [27], at least for momentum transfers less than  $1 \text{ GeV}^2$ . (The region of validity is mainly constrained by limitations of the bag model.) In order to reduce the theoretical uncertainties at higher momentum transfer, which is also of experimental interest, we prefer to show the ratios of the form factors with respect to corresponding free space values.

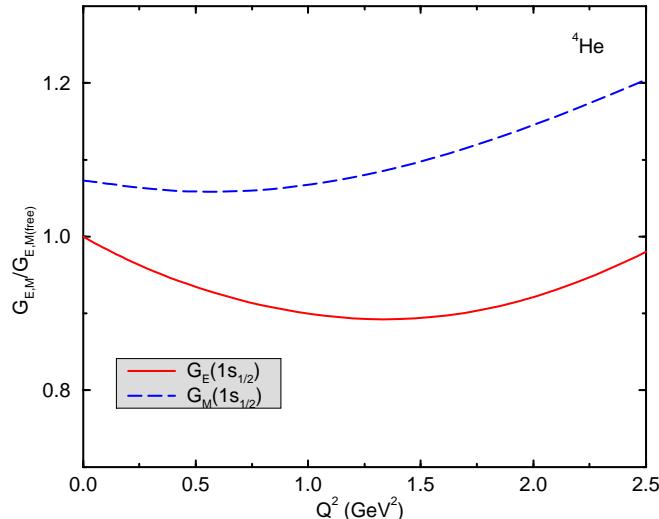


FIG. 1. Ratio of in-medium to free space electric and magnetic form factors of the proton in  $^4\text{He}$ . (The free bag radius was taken to be  $R_0 = 0.8 \text{ fm}$ .)

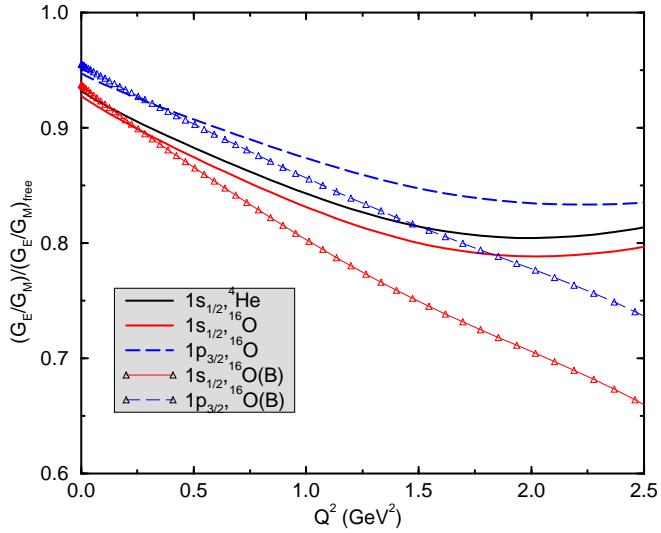


FIG. 2. Ratio of electric and magnetic form factors in-medium divided by free space ratio. As in previous figure, curves with triangle symbols represent corresponding values calculated in a variant of QMC with a 10% reduction of  $B$ .

Fig. 1 shows the ratio of the electric and magnetic form factors with respect to the free space values for  $^4He$  (only one state,  $1s_{1/2}$ ). As expected, both the electric and magnetic rms radii become slightly larger and the magnetic moment of the proton increases by about 7%. Although we cannot show the results for lack of space, we have made similar calculations for  $^{16}O$ , where the momentum dependence of the form factors for the  $1s$ -orbit nucleon is more suppressed than that for the  $1p$ -states. This is because the inner orbit experiences a larger average baryon density. The magnetic moment of the nucleon in the  $1s$ -orbit is similar to that in  $^4He$ , but it is reduced by 2–3% in the  $1p$ -orbits. The difference between two  $1p$ -orbits is rather small.

From the experimental point of view, we note that the ratio  $G_E/G_M$  can be derived directly from the ratio of transverse to longitudinal polarization of the outgoing proton, with minimal systematic errors. We find that  $G_E/G_M$  (for a proton in  $^4He$ ) runs roughly from 0.41 at  $Q^2 = 0$  to 0.28 at  $Q^2 = 1 \text{ GeV}^2$ . The ratio of  $G_E/G_M$  with respect to the corresponding free space ratio is presented in Fig. 2. The result for the  $1s$ -orbit in  $^{16}O$  is close to that in  $^4He$  and 2% lower than that for the  $p$ -orbits in  $^{16}O$ . In order to interpolate smoothly between the confined and deconfined phases as the baryon density increases, it has been

suggested that the bag constant might decrease with increasing density. As we see in Fig. 2 the effect of a possible reduction in  $B$  has a significant effect on this ratio of ratios, especially for larger  $Q^2$ .

For completeness, we have also calculated the orbital electric and magnetic form factors for heavy nuclei such as  $^{40}Ca$  and  $^{208}Pb$ . Because of the larger central baryon density of heavy nuclei, the proton electric and magnetic form factors in the inner orbits ( $1s_{1/2}$ ,  $1p_{3/2}$  and  $1p_{1/2}$  orbits) suffer much stronger medium modifications than those in light nuclei. That is to say, the  $Q^2$  dependence is further suppressed, while the magnetic moments appear to be larger. Surprisingly, the nucleons in peripheral orbits ( $1d_{5/2}$ ,  $2s_{1/2}$ , and  $1d_{3/2}$  for  $^{40}Ca$  and  $2d_{3/2}$ ,  $1h_{11/2}$ , and  $3s_{1/2}$  for  $^{208}Pb$ ) still endure significant medium effects ( $1d_{3/2}$  overlaps with  $1d_{5/2}$  and  $3s_{1/2}$  overlaps with  $2d_{3/2}$ ), and are comparable to those in  $^4He$ .

#### IV. OMEGA-MESIC NUCLEI

As we explained in the introduction there is great interest in the medium modification of the light vector ( $\rho$ ,  $\omega$  and  $\phi$ ) meson masses. In earlier work with the QMC model we have investigated changes of meson properties in the nuclear medium – notably, the effective mass of the  $\rho$  meson formed in light nuclei and properties of the kaons in nuclear matter [28]. However, we have only recently tackled the question of whether meson-nucleus bound states are possible in the model [25].

At position  $\vec{r}$  in a nucleus (the coordinate origin is taken as the center of the nucleus), the Dirac equations for the quarks and antiquarks in the  $\omega$  meson bag are given by [28]:

$$\left[ i\gamma \cdot \partial - (m_q - V_\sigma(\vec{r})) \mp \gamma^0 \left( V_\omega(\vec{r}) + \frac{1}{2} V_\rho(\vec{r}) \right) \right] \begin{pmatrix} \psi_u(\vec{r}) \\ \psi_{\bar{u}}(\vec{r}) \end{pmatrix} = 0, \quad (3)$$

$$\left[ i\gamma \cdot \partial - (m_q - V_\sigma(\vec{r})) \mp \gamma^0 \left( V_\omega(\vec{r}) - \frac{1}{2} V_\rho(\vec{r}) \right) \right] \begin{pmatrix} \psi_d(\vec{r}) \\ \psi_{\bar{d}}(\vec{r}) \end{pmatrix} = 0, \quad (4)$$

$$[i\gamma \cdot \partial - m_s] \psi_s(\vec{r}) \text{ (or } \psi_{\bar{s}}(\vec{r})\text{)} = 0, \quad (5)$$

where  $V_\sigma(\vec{r}) = g_\sigma^q \sigma(\vec{r})$ ,  $V_\omega(\vec{r}) = g_\omega^q \omega(\vec{r})$  and  $V_\rho(\vec{r}) = g_\rho^q b(\vec{r})$  are the mean-field potentials at the position  $\vec{r}$ , and are calculated self-consistently, as we explained earlier. Hereafter we use the notation,  $\omega_B$ , to specify the physical, bound  $\omega$  meson, in order to avoid confusion with the isoscalar-vector  $\omega$  field appearing in QMC (or QHD). The bag radius in medium,  $R^*$ , is determined self-consistently through the stability condition for the (in-medium) mass of the meson against the variation of the bag radius.

The eigenenergies in units of  $1/R^*$ ,  $\epsilon_f$  ( $f = u, \bar{u}, d, \bar{d}$ ), are given by

$$\begin{pmatrix} \epsilon_u(\vec{r}) \\ \epsilon_{\bar{u}}(\vec{r}) \end{pmatrix} = \Omega_q^*(\vec{r}) \pm R^* \left( V_\omega(\vec{r}) + \frac{1}{2} V_\rho(\vec{r}) \right), \quad (6)$$

$$\begin{pmatrix} \epsilon_d(\vec{r}) \\ \epsilon_{\bar{d}}(\vec{r}) \end{pmatrix} = \Omega_q^*(\vec{r}) \pm R^* \left( V_\omega(\vec{r}) - \frac{1}{2} V_\rho(\vec{r}) \right), \quad (7)$$

where  $\Omega_q^*(\vec{r}) = \sqrt{x_q^2 + (R^* m_q^*)^2}$ , with  $m_q^* = m_q - g_\sigma^q \sigma(\vec{r})$  ( $q = u, \bar{u}, d, \bar{d}$ ). The bag eigenfrequencies,  $x_q$ , are determined by the usual, linear boundary condition [28].

The physical  $\omega_B$  meson is a superposition of the octet and singlet states with the mixing angle,  $\theta_V = 39^\circ$ , as estimated by Particle Data Group. We assume that the value of the mixing angle does not change in medium, although this is possible and merits further investigation. We self-consistently calculate the effective mass,  $m_{\omega_B}^*(\vec{r})$  at the position  $\vec{r}$  in the nucleus. Because the vector potentials for the same flavor of quark and antiquark cancel each other, the potentials for the  $\omega_B$  meson is given by  $m_{\omega_B}^*(r) - m_{\omega_B}$ , which depends only on the distance from the center of the nucleus,  $r = |\vec{r}|$ .

The depth of the potential felt by the  $\omega$  meson is typically more than 100 MeV. Because the typical momentum of the bound  $\omega$  is low, it should be a very good approximation to neglect the possible energy difference between the longitudinal and transverse components of the  $\omega$  [17]. Imposing the Lorentz condition,  $\partial_\mu \phi^\mu = 0$ , solving the Proca equation becomes equivalent to solving the Klein-Gordon equation. Thus, to obtain the meson nucleus binding energies, we may solve the Klein-Gordon equation.

An additional complication, which has so far been ignored, is the meson absorption in the nucleus. This requires an imaginary part for the potential to describe the effect. At the moment, we have not been able to calculate the in-medium widths of the mesons, or the imaginary part of the potential in medium, self-consistently within the model. In order to make a more realistic estimate for the meson-nucleus bound states, we therefore include the width of the  $\omega_B$  meson in the nucleus phenomenologically:

$$\tilde{m}_{\omega_B}^*(r) = m_{\omega_B}^*(r) - \frac{i}{2} [(m_{\omega_B} - m_{\omega_B}^*(r)) \gamma_{\omega_B} + \Gamma_{\omega_B}], \quad (8)$$

$$\equiv m_{\omega_B}^*(r) - \frac{i}{2} \Gamma_{\omega_B}^*(r), \quad (9)$$

where,  $m_{\omega_B}$  and  $\Gamma_{\omega_B}$  is the corresponding mass and width in free space. In Eq. (8)  $\gamma_{\omega_B}$  is treated as a phenomenological parameter to describe the in-medium meson width,  $\Gamma_{\omega_B}^*(r) \equiv (m_{\omega_B} - m_{\omega_B}^*(r)) \gamma_{\omega_B} + \Gamma_{\omega_B}$ . According to the estimates in Refs. [16,23], the width of the  $\omega_B$  meson at normal nuclear matter

density is  $\Gamma_{\omega_B}^* \sim 30 - 40$  MeV. Thus, we calculate the single-particle energies using the values for the parameters appearing in Eq. (8),  $\gamma_{\omega_B} = 0, 0.2, 0.4$ , which cover the estimated ranges. Thus we actually solve the following Klein-Gordon equation:

$$[\nabla^2 + E_{\omega_B}^2 - \tilde{m}_{\omega_B}^{*2}(r)] \phi_{\omega_B}(\vec{r}) = 0. \quad (10)$$

Equation (10) has been solved in momentum space, using the method developed in Ref. [29]. To confirm the calculated results, we also calculated the single-particle energies by solving the Schrödinger equation. Calculated single-particle energies for the  $\omega_B$  meson, obtained by solving the Klein-Gordon equation are listed in Table I. We should mention that the advantage of solving the Klein-Gordon equation in momentum space is that it can handle quadratic terms arising in the potentials without any trouble.

TABLE I. Calculated  $\omega$  meson single-particle energies,  $E = \text{Re}(E_\omega - m_\omega)$ , and full widths,  $\Gamma$ , (both in MeV) in various nuclei, where the complex eigenenergies are,  $E_\omega = E + m_\omega - i\Gamma/2$ . See Eq. (8) for the definition of  $\gamma_\omega$ . In the light of the estimates of  $\Gamma$  in Refs. [16], the results with  $\gamma_\omega = 0.2$  are expected to correspond best with experiment.

	$\gamma_\omega=0$		$\gamma_\omega=0.2$		$\gamma_\omega=0.4$	
	$E$	$\Gamma$	$E$	$\Gamma$	$E$	$\Gamma$
$^{16}_\omega\text{O}$	1s	-93.5	8.14	-93.4	30.6	-93.4
	1p	-64.8	7.94	-64.7	27.8	-64.6
$^{40}_\omega\text{Ca}$	1s	-111	8.22	-111	33.1	-111
	1p	-90.8	8.07	-90.8	31.0	-90.7
	2s	-65.6	7.86	-65.5	28.9	-65.4
$^{90}_\omega\text{Zr}$	1s	-117	8.30	-117	33.4	-117
	1p	-105	8.19	-105	32.3	-105
	2s	-86.4	8.03	-86.4	30.7	-86.4
$^{208}_\omega\text{Pb}$	1s	-118	8.35	-118	33.1	-118
	1p	-111	8.28	-111	32.5	-111
	2s	-100	8.17	-100	31.7	-100
$^6_\omega\text{He}$	1s	-55.7	8.05	-55.6	24.7	-55.4
$^{11}_\omega\text{B}$	1s	-80.8	8.10	-80.8	28.8	-80.6
$^{26}_\omega\text{Mg}$	1s	-99.7	8.21	-99.7	31.1	-99.7
	1p	-78.5	8.02	-78.5	29.4	-78.4
	2s	-42.9	7.87	-42.8	24.8	-42.5

Our results strongly support the suggestion of Hayano *et al.* that one should find bound  $\omega$ -nuclear states [23,24]. For a large atomic number nucleus and a relatively wide range of the in-medium meson widths, it seems inevitable that one should find such  $\omega$ -nucleus bound states, bound by 50-100 MeV. For a more consistent treatment, we would like to calculate the in-medium meson width within the QMC model self-consistently. We would also need to take into account the  $\sigma$ - $\omega$  mixing effect which is very interesting, and especially important at higher densities [17].

## V. CONCLUSION

In summary, we have calculated the electric and magnetic form factors for the proton bound in specific orbits for several closed shell finite nuclei. Generally the electromagnetic rms radii and the magnetic moments of the bound proton are increased by the medium modifications. The form factors corresponding to different orbits appear to behave quite differently. While the difference between the nucleon form factors for orbits split by the spin-orbit force is very small, the difference between inner and peripheral orbits is considerable. In view of current experimental developments, including the ability to precisely measure elastic and quasielastic electron-nucleus scattering polarization observables, it should be possible to detect differences between the form factors in different shell model orbits. The current and future experiments at TJNAF and Mainz therefore promise to provide vital information with which to guide and constrain dynamic microscopic models for finite nuclei, and perhaps unambiguously isolate a signature for the role of quarks.

We have also calculated the single-particle energies for  $\eta$ - and  $\omega$ -mesic nuclei using QMC. Here we reported only the results for the  $\omega$ . The potentials for the mesons in the nucleus were calculated self-consistently, in local density approximation, by embedding the MIT bag model  $\omega$  meson in the nucleus described by solving mean-field equations of motion. Although the specific form for the width of the in-medium meson could not be calculated in this model, our results suggest that one should find deeply bound  $\omega$ -nucleus states for a relatively wide range of the in-medium meson widths. In the near future, we plan to calculate the in-medium  $\omega$  width self-consistently in the QMC model.

### Acknowledgment

This work was supported by the Australian Research Council.

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